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RENEWABLE ENERGY SOURCES IN HEAT PUMPS FOR ENERGY EFFICIENT LOW-TEMPERATURE DRYING OF SEED GRAIN

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Abstract. *High energy costs for the process of drying seed grain materials require the development of advanced energy-efficient technologies. Drying seed materials requires soft drying modes, so it is not possible to dry them at high temperatures, which is related to the quality of the material. The analyzed methods of drying rapeseed indicate that the main method of drying is convective. There is a problem with high energy costs for the process, which is associated with low-temperature drying and the imperfection of existing drying equipment. Also, existing drying methods such as sublimation, infrared, microwave and ultrasonic in this case will significantly affect the quality of the material, so it is undesirable to use them. Therefore, to enhance the intensity of drying, if it is necessary to create a low-temperature drying process, the condensation method of drying is employed, alongside a reduction in the moisture content of the heat carrier.*

The application of this technology solves a number of tasks, such as: economy, environmental friendliness, manufacturability and operational expediency of the drying unit. The presented research solves the urgent task of intensity and economy, preservation of all seed properties of the material, using the example of rapeseed. Based on the presented tasks for improving the operation of the seed dryer, an installation with an installed heat generator on a heat pump (HP) was developed, which allows for implementing and solving all the stated tasks.

As a result of the research, when comparing a drying plant with a heat pump to a drying plant with electric heating by electric heaters, the quality of rapeseed improved by 3%, the specific heat consumption decreased by 3.3 times, the intensity increased by 13%, the efficiency of the drying plant with the heat pump increased to 58.4 %.

Keywords: *energy efficiency, drying unit, heat pump, germination, rapeseed.*

ВІДНОВЛЮВАНІ ДЖЕРЕЛА ЕНЕРГІЇ В ТЕПЛОВИХ НАСОСАХ ДЛЯ ЕНЕРГОЕФЕКТИВНОГО НИЗЬКОТЕМПЕРАТУРНОГО СУШІННЯ НАСІННЄВОГО ЗЕРНА

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Анотація. *Високі енергетичні витрати на процес сушіння насіннєвих зернових матеріалів вимагає розробки передових енергоефективних технологій. Сушіння насіннєвих матеріалів вимагає м'яких режимів сушіння, тобто неможливо їх сушити при високих температурах, що пов'язано з якістю матеріалу. Проаналізовані способи сушіння насіння ріпаку вказують на те, що основним способом сушіння є конвективне.*

Існує проблема з високими енергетичними витратами на процес, що пов'язано з низькотемпературним сушінням і недосконалістю існуючого сушильного обладнання. Також існуючи методи сушіння, такі як сублімаційний, інфрачервоний, мікрохвильовий та ультразвуковий в даному випадку істотно вплинуть на якість матеріалу, тому їх небажано застосовувати. Тому для підвищення інтенсивності сушіння, при необхідності створення низькотемпературного процесу сушіння, використовують конденсаційний спосіб сушіння із зниженням вологовмісту теплоносія.
Застосування цієї технології вирішують ряд завдань, таких як: економічність, екологічність, технологічність та експлуатаційна доцільність сушильної установки. Представлені дослідження вирішують актуальне завдання інтенсивності та економічності, збереження всіх насіннєвих властивостей матеріалу на прикладі насіння ріпаку. Виходячи з представлених завдань із покращення роботи насіннєвої сушарки розроблена установка із встановленим теплогенератором на тепловому насосі (ТН), яка дозволяє реалізувати та вирішити всі заявлені завдання.
В результаті проведених досліджень, при порівнянні сушильної установки із ТН та сушильної установки з електропідігрівом електрокалориферами, якість насіння ріпаку покращилось на 3%, питомі витрати теплоти знизились в 3,3 раз, інтенсивність збільшилась на 13%, к.к.д. сушильної установки із тепловим насосом збільшилось до 58,4%.
Бібл. 30, рис. 5, табл. 2.

Ключові слова: *енергоефективність, сушильна установка, тепловий насос, схожість, насіння ріпаку.*

Introduction. At the current stage of the development of grain drying in the world, there is an urgent need to create and develop highly efficient grain drying equipment that would ensure minimal energy consumption and high seed germination.

The urgency of the problem of energy saving during dehydration is related to large volumes of grain: from 50% to 80%, and in adverse weather conditions even 100% of the annually grown grain requires drying. On average, when drying 1 ton of grain, it is necessary to remove 70 to 80 kg of moisture, which with a harvest of 35 to 40 million tons leads to costs of 0.4 to 0.7 million tons of conventional fuel and significant labor costs. The time spent on drying grain is up to 70% of the time of harvesting.

The drying process is regulated by the maximum heating temperature of the seed material, which should not exceed 43 – 45 °C [1-5]. Our preliminary research on determining the maximum heating temperature of seed material on the modern winter rapeseed variety Svitoch (Vinnytsia Research Station, Ukraine) showed that it is possible to carry out drying up to a grain temperature of 48 °C, at which seed germination is 97% (heat carrier temperature 50 °C). [6].

Energy costs when drying food grain in modern and modernized dryers, the heat consumption can be about 4800-5000 kJ/kg of evaporated moisture, and when drying seeds, the costs increase by 30-40% or more, which is mainly caused by low drying temperatures [6].

When drying seed material, it is not possible to intensify the process by increasing the temperature of the coolant. Therefore, there is a need to use another method of intensification, which is achieved by reducing the moisture content of the heat carrier, which in turn increases the drying speed and reduces the duration of the process.

The purpose of the work is to create advanced energy-efficient low-temperature seed grain drying technologies.

The winter rapeseed variety Svitoch (Vinnytsia Experimental Station, Ukraine) and a grain drying unit with a heat pump with a capacity of 20 kg/h were selected as the object of drying.

During the research, experimental methods and state-of-the-art means were used to measure drying parameters with the help of an automated system for collecting and processing information in a developed program on a specially designed and manufactured installation, and the obtained data were processed in modern integrated Excel and Mathcad systems. To assess the quality of rapeseed, the standard research methods provided for by DSTU 4138 - 2002 were used. Theoretical studies were carried out taking into account the methods based on the main provisions of the theory of heat and mass transfer, the theory of similarity, which were processed with the help of computer technologies.

Rapeseed moisture is calculated as a percentage:

$$W = \frac{m_2 - m_3}{m_2 - m_1} \cdot 100\%, \quad (1)$$

where m_1 – mass of an empty box (with a lid), g;

m_2 – the mass of the box with the sample before drying, g;

m_3 – weight of the sample after drying, g.

To carry out research, a drying plant with HP was developed at the Institute of Engineering Thermophysics of the National Academy of Science of Ukraine (Fig. 1). Technical characteristics of the grain drying plant with HP are presented in the Table 1.

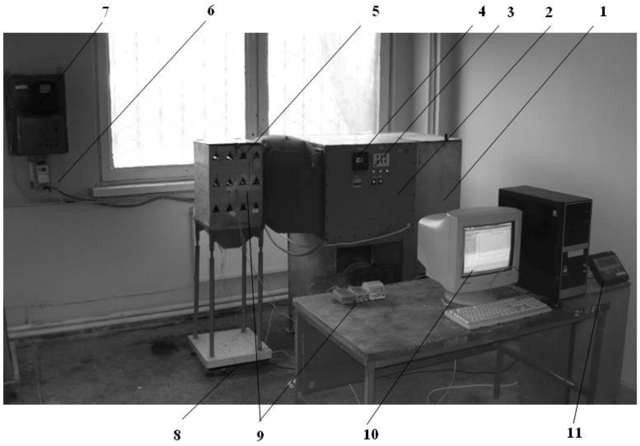

Fig. 1. Experimental plant with HP for drying rapeseed:

1 – heat pump unit; 2 – control panel; 3 – time relay; 4 – thermal relay; 5 – drying shaft; 6 – speed regulator; 7 – electricity meter; 8 – scales; 9 – i-7018 analog-to-digital converter, i-7520 interface converter and chromel-copel thermoelectric converters; 10 computer; 11 – digital display of scales

Table 1. Technical characteristics of the grain drying plant with HP

1.	Productivity in terms of extracted moisture	2 kg/h
2.	The temperature of the coolant at the entrance to the drying chamber	35 – 55 °C
3.	Refrigerant evaporation temperature	0 – +5 °C
4.	Refrigerant	R22
5.	The moisture content of the coolant at the entrance to the drying chamber	6 g/kg dry air
6.	Heat carrier costs	250 – 800 m^3/h
7.	Overall dimensions: • drying chamber • heat pump unit	 0,32x0,32x0,48 m 0,7x0,9x1,3 m
8.	Compressor ZR49K3E – TFD: • cooling capacity • power of the electric motor of the compressor	 11,21 kW 4,08 kW
9.	Circulation fan Ц14-46 № 2,5 • power of the electric motor • the number of revolutions	 0,75 kW 1450 rpm

Methodology for conducting an experiment on a drying plant with HP:

1. Before conducting experiments, we determine the initial moisture content of rapeseed according to the formula 1. The rapeseed is poured into boxes and dried in a laboratory dryer at a temperature of 105 °C for 5 hours. Cool in a desiccator with silica gel to prevent sorption of moisture from the air.

2. Conducting the experiment begins with turning on the grain dryer with a heat pump and the computer system for collecting and processing information, which continuously records the time of the experiment, the temperature of the drying agent, the temperature on the surface and in the middle of the material layer, the change in the weight of the sample.

3. After installation in a drying unit with HP drying mode, a batch of seed rape is poured into a drying shaft and dried to the final moisture content of rape – 8 %.

4. Two samples are taken from the batch of dried rape seed obtained:

4.1. The first sample is used to determine the seed properties of the material

4.2. The second - determines the final moisture content of the material by formula 1.

5. After determining the moisture content of the sample after drying, we calculate and construct the drying curves and drying speed of rapeseed: $W = f(\tau)$, $dW/d\tau = f(W)$.

Methods of analysis of the germination of rape seeds:

1. Thermostats once every 10 days, and dishes before each analysis are washed with hot water and detergents and disinfected with a 1% solution of potassium permanganate or alcohol. A tray with water is placed in the working chamber of the thermostat. Petri dishes are sterilized in an oven at a temperature of (130 +2) °C for an hour.

2. Germination analysis is carried out on rapeseed seeds isolated during the determination of purity. For this purpose, 100 seeds are arbitrarily counted. Seeds are evenly placed on moistened filter paper. Analysis of seeds is carried out on one layer of moistened paper placed in Petri dishes. Petri dishes are covered with glass plates or lids.

3. Analysis of rape seed germination under different drying modes is carried out at a temperature of 20 °C for 7 days. We determine the energy of germination and germination of seeds on abnormal seedlings (damaged, weak, rotten, underdeveloped and dead) on the 2nd, 4th and 7th day, respectively.

The given methods make it possible to analyze the obtained research results with the aim of determining an energy-efficient rational mode of drying rapeseed.

Results and Discussion. Experimental studies were carried out in the following stages:

The first stage. Setting the effective moisture content of the heat carrier in the dryer with HP.

Determination of the value of the required moisture parameter of the heat carrier when drying rapeseed in a drying unit with a heat pump was carried out according to the I - d diagram on the saturation line ϕ = 100% and was chosen depending on the temperature of the evaporator HP (Fig. 2).

The conversion factor of the heat pump also depends on the temperature of the evaporator and the HP condenser (Fig. 3).

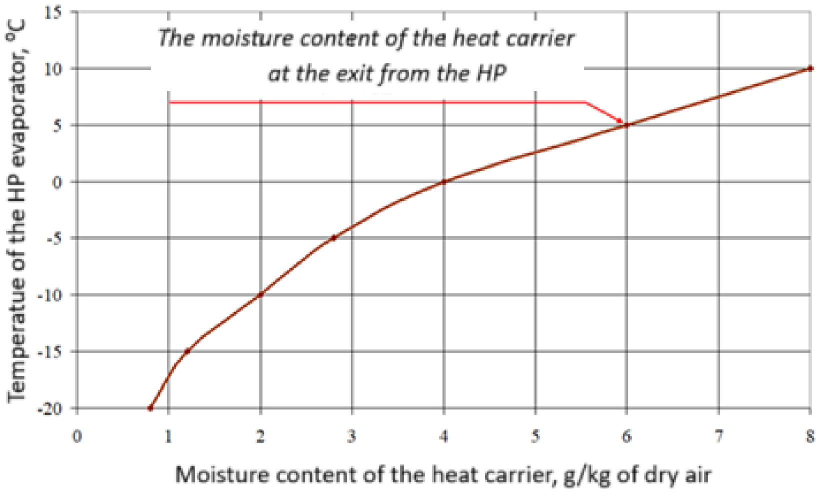

Fig. 2. Dependence of the moisture content of the heat carrier on the temperature of the HP evaporator with the ZR49K3E - TFD Copeland ZR compressor when working on R 22 freon

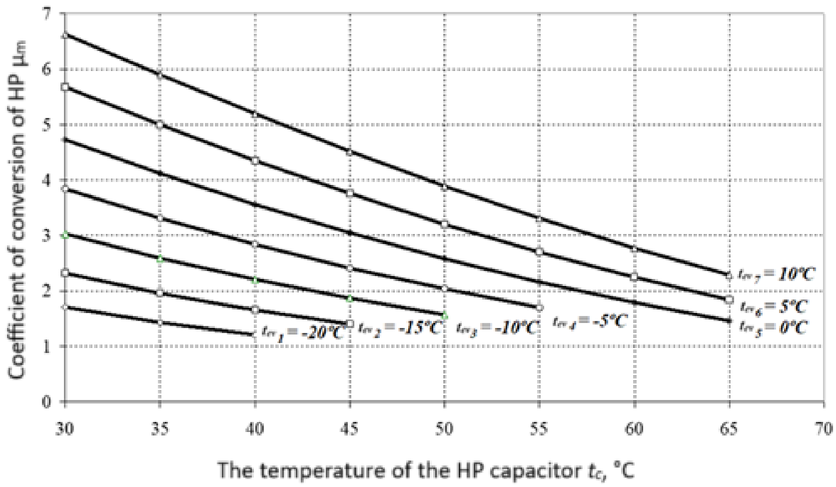

Fig. 3. Dependence of the conversion coefficient on the temperature change of the evaporator and condenser of the HP with the ZR49K3E compressor - TFD of the Copeland ZR company when operating on R 22 freon

Determination of the moisture content of the heat carrier in the heat pump can be adjusted and depends on the temperatures at the condenser and the HP evaporator. Determination of the moisture content of the heat carrier is carried out by comprehensively analyzing figures 2,3. The value of the moisture content is limited (Fig. 2) by the temperature of the evaporator of the heat pump (it must be higher than the temperature of 0 °C, so that the evaporator does not freeze) and the temperature of the HP condenser (the necessary optimal operating temperature HP (obtained according to our own research) for seed grain is 50 °C). An increase in the temperature of the HP evaporator increases the moisture content of the coolant (Fig. 2) and the HP conversion factor (μ) (Fig. 3). To increase the intensity of drying, it is necessary to reduce the moisture content of the heat carrier, and to increase energy efficiency, the conversion factor of HP should be increased. Therefore, the optimal operation mode of HP is determined: the temperature of the HP evaporator is 5 °C, the temperature of the HP condenser is 50 °C, the moisture content of the heat carrier is d = 6 g/kg evaporated moisture, the HP conversion factor is μ = 3.2.

II stage. Increasing the intensity of drying rapeseed in a drying unit with HP.

The study of the effectiveness of the rape seed drying process in a condensation drying unit with HP is carried out by comparing it with the usual convective drying method with electric heating (instead of HP, a block of heaters with a capacity of 7.5 kW is installed). That is, the moisture content of the heat carrier at the exit from the heat pump is 6 g/kg dry air and we compare it with the moisture content of the environment without a heat pump of 10 g/kg dry air with heating of the coolant with the help of electric heaters.

From Fig. 4 shows that a decrease in the moisture content of the heat carrier accelerates the drying time of rapeseed by 13%. The final temperature of the heat carrier in a 20 mm layer of rapeseed and with a final grain moisture content of 8% is 40.9 °C, with electric heating - 41.2 °C.

The kinetics of the rapeseed drying process according to the obtained experimental data were described using polynomials of the 2nd degree (1 – 2) with the reliability of the approximation R2 = 0.9998.

For air moisture content d = 6 g/kg dry air with a heat pump:

$$W_6 = 0{,}0017\tau^2 - 0{,}2978\tau + 19{,}346 \quad (2)$$

For air moisture content d = 10 g/kg dry air with electric heating:

$$W_{10} = 0{,}0012\tau^2 - 0{,}2855\tau + 19{,}32 \quad (3)$$

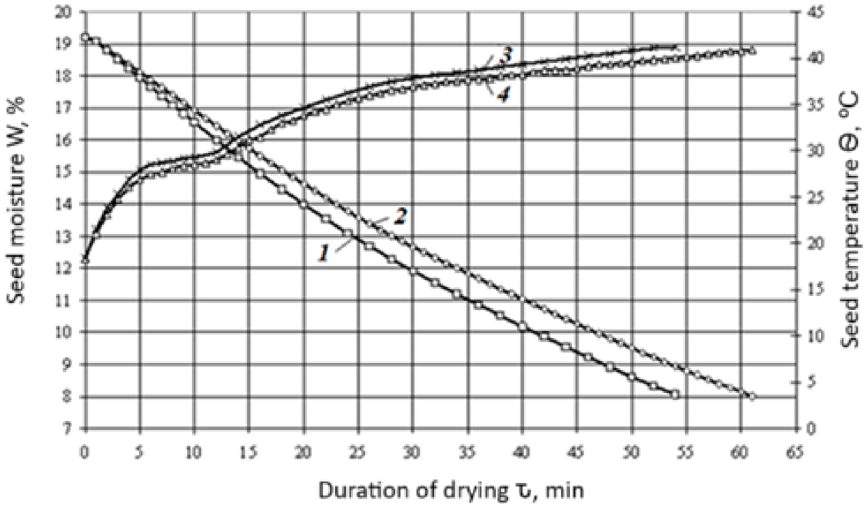

Fig. 4. Kinetics of the process and temperature curves of rape seed drying with:
1,3 – heat pump (d = 6 g/ kg dry air, μ_m = 3,2); 2,4 – electric heating (d = 10 g/ kg dry air).
t = 50 °C, V = 1,2 m/s, Win = 19,2%, δ = 20 mm

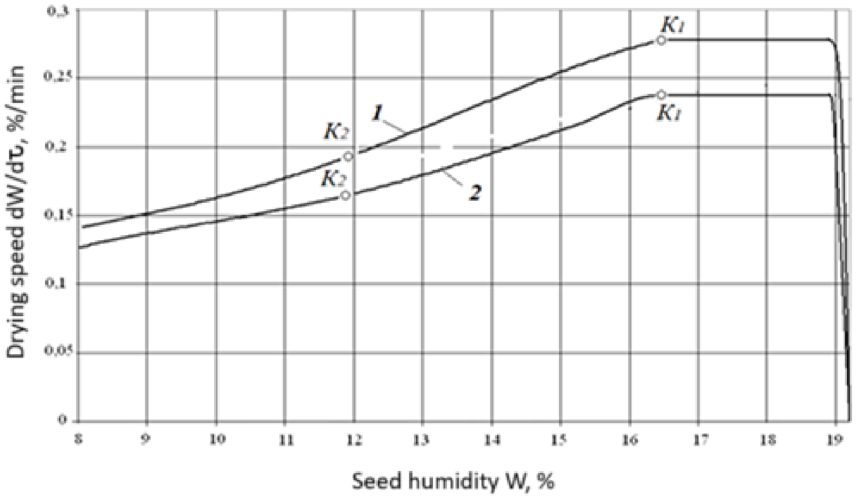

Fig. 5. Rapeseed drying speed curves at different moisture contents of the coolant:
1 – heat pump (d = 6 g/ kg dry air, μm = 3,2); 2 – electric heating (d = 10 g/ kg dry air).
t = 50 °C, V = 1,2 m/s, Win = 19,2%, δ = 20 mm

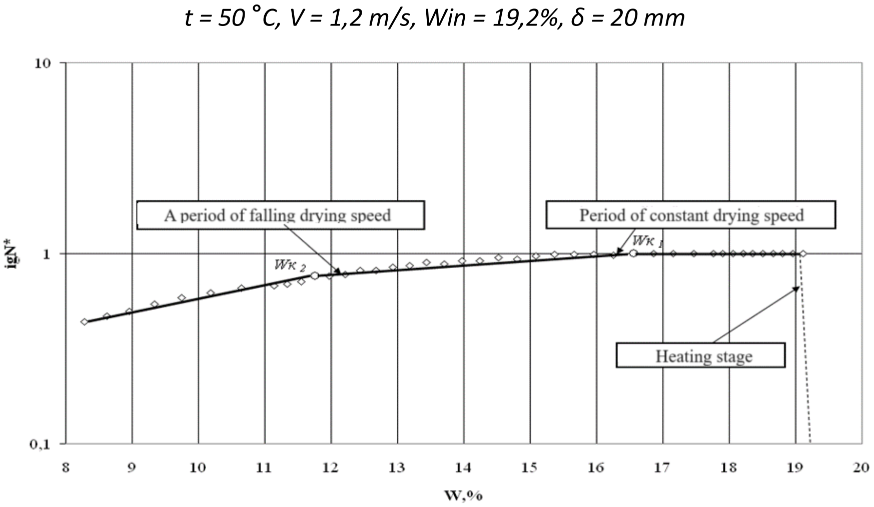

Fig. 6. Generalized curve of rape seed drying speed in semi-logarithmic coordinates

As can be seen from the drying speed curves, the drying of rapeseed with different moisture content of the heat carrier goes through periods of heating, constant and falling drying speed (Fig. 5). The lower the moisture content of the air, the faster the rapeseed drying rate. The maximum rate of rapeseed drying at the air moisture content of 6 g/kg dry air, at the end of the period of constant drying speed, at the critical point K_1 is 0.283%/min, and at the air moisture content of 10 g/kg dry air – 0.243%/min., which is less by 14.2%. At point K_2, the difference in drying speed is 4.4%, and at the end of the period of falling drying speed, this difference decreased by 3.0%.

To describe the drying process of rapeseed, a generalized drying speed curve was constructed in semi-logarithmic coordinates (Fig. 6).

When drying rapeseed in a drying unit with HP, at the beginning of the process, the material is briefly heated, then it is dried in a period of constant drying speed and at the end in a period of falling drying speed, which consists of two stages.

It can also be seen from the generalized curve of rape seed drying speed constructed in semi-logarithmic coordinates that it is a broken line, the break of which occurs at moisture content W_{K_1} = 16.6% and humidity W_{k_2}= 11.8%. The law of change of N^* *(dW/dτ)* during the transition of constant drying speed to 1 and 2 periods of falling drying speed changes, which indicates a difference in the kinetics of drying in different parts of the second period

The value of N^*, not taking into account the heating stage in the period of constant drying speed, has a linear dependence:

$$N^* = 1, \tag{4}$$

$$16{,}6 \le W \le 19{,}2$$

in the 1st part of the second period is determined by the following empirical dependence:

$$N^* = 0{,}2713 e^{0{,}0852} W, \tag{5}$$

$$11{,}8 \le W \le 16{,}6$$

in the second part of the second period is equal:

$$N^* = 0{,}0927 e^{0{,}1867} W, \tag{6}$$

$$8{,}0 \le W \le 11{,}8$$

III stage. Increasing the energy efficiency of rape seed drying in a drying plant with HP.

Energy consumption was estimated by specific heat consumption per kg of evaporated moisture during drying in a drying plant with HP. The specific heat consumption in the drying plant with HP was recorded based on the change in electricity consumption on the meter and the change in mass during drying on the scales installed under the drying shaft. The main characteristics of the rapeseed drying process are the time of the experiment and the moisture content of the material, therefore, to characterize the energy costs of the drying process, we cite two dependencies: *Q= f (τ)* and *Q= f (W)* and their obtained equations (Fig. 7, 8).

We describe Fig. 8 starting from 3 min, so at the beginning of the rapeseed drying process, the specific heat consumption for 3 min (at a humidity of 18.4%) is 3272 kJ/kg of evaporated moisture, then the heat consumption increases in the middle of the process for 28 min (at a humidity of 12.1%) they amount to 3,600 kJ/kg of evaporated moisture, that is the increase occurred by 10% or by 13.12 kJ/min or by 52 kJ/% humidity. The process continues from 28 to 54 min (from moisture content 12.1 to 8%), where the intensity of drying decreases and the specific heat consumption increases by 24.4% or by 33.84 kJ/min or by 214.63 kJ/% moisture content. The total increase in specific heat consumption during drying of rapeseed at a drying time of 54 minutes is 36.9%.

That is, based on the results of research, the specific heat consumption during drying of rapeseed from the initial moisture content of 19.2% to the final moisture content of 8% is 4480 kJ/kg of evaporated moisture or 467kJ/kg of dry product.

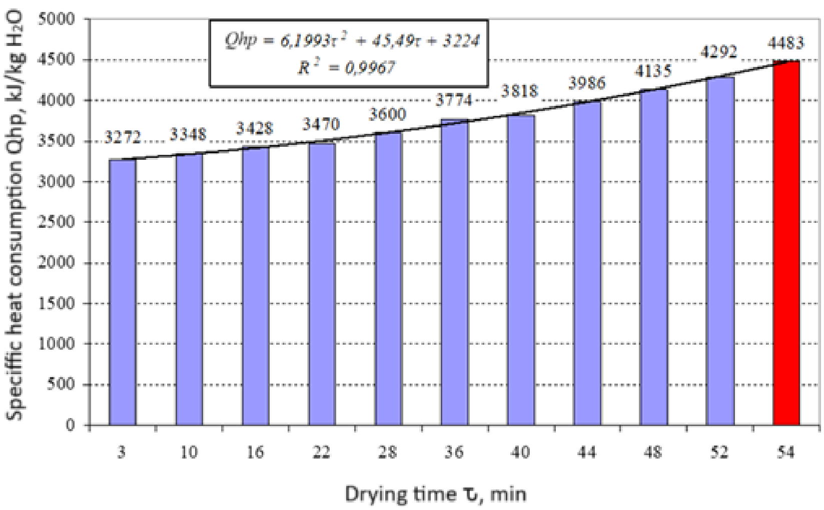

Fig. 7. Specific heat consumption from the time of the experiment in the drying unit with HP: t = 50 °C, V = 1,2 m/s, Win = 19,2%, δ = 20 mm, d = 6 g/ kg dry air, μ_m = 3,2

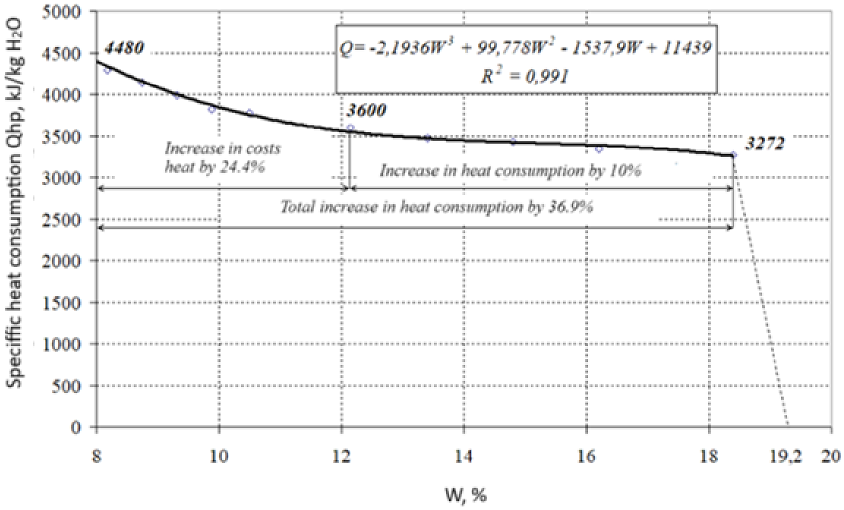

Fig. 8. Specific heat consumption from material humidity in a drying unit with HP: t = 50 °C, V = 1,2 m/s, Win = 19,2%, δ = 20 mm, d = 6 g/kg dry air., μ_m = 3,2

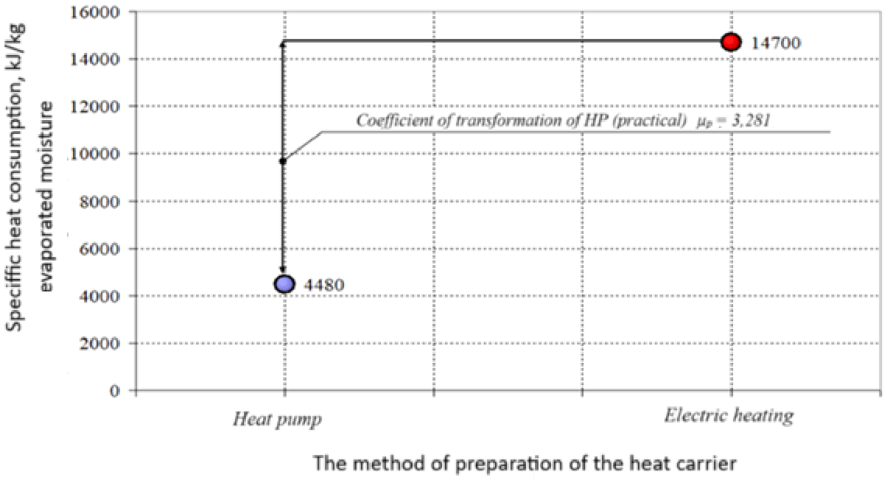

Fig. 9. Comparison of specific heat consumption from the method of preparation of the heat carrier

Comparing the specific heat consumption during drying of rapeseed in a drying plant with different methods of preparing the heat carrier, the heat pump, compared to the usual heating of the heat carrier in the heater, allows to reduce energy consumption by 3.281 times (Fig. 9).

The value of reduced heat energy consumption μ_p = 3,281 and there is an established practical HP conversion factor, which differs from the theoretical one established when selecting the drying mode (according to TN operation schedules on R 22 freon, Fig. 4, 5) μ_m = 3,2. The difference is 2.5 %.

The evaluation of the quality of the dryer is evaluated by its energy coefficient of useful action η (coefficient of useful action), which is determined by the ratio of useful energy Q_{useful} to all the energy spent on the process Q_{spent}:

$$\eta = \frac{Q_{useful}}{Q_{spent}} = \frac{r + \Delta r}{Q_{calor}} = \frac{2382 + 238}{4480} = 58{,}4 \quad (7)$$

where: r – specific heat of evaporation of moisture, kJ/kg.

Q *calor* – energy spent on heating the heat carrier in the heater, kJ/kg of evaporated moisture.

From the given calculation in formula 5 coefficient of useful action drying plant with HP is η = 53.2, and with electric heating η = 16.2.

IV stage. Comparison of the intensity and energy efficiency of rape seed drying in a drying plant with HP.

The intensity of the rape seed drying process in a heat pump grain dryer can be estimated by the moisture elasticity of the volume of the dryer, that is the amount of moisture evaporated from 1 m^3 of its volume per hour.

If we compare the change in drying intensity and the specific heat consumption from the moisture content of rapeseed in the drying mode t = 50 °C, V = 1.2 m/s, δ = 20 mm, d = 6 g/kg dry air, we can observe the following dependence: at the beginning of the drying process, the intensity is high - the specific heat consumption is small, gradually the intensity decreases, and the consumption increases (Fig. 10). The optimal value of the intensity of 36 kg/m^3 h and the average specific heat consumption of 3675 kJ/kg is at point K_2 at a humidity of 11.8 %.

Comparing the obtained data on the average intensity of the heat pump grain dryer with direct flow mine grain dryers, the intensity of the process increases by 1.5-2 times (Table 2).

V stage. Rapeseed seed quality after drying in a drying unit with HP.

The similarity of rapeseed in the drying plant with HP in relation to the original rapeseed is 100%, which indicates the high quality of the drying process (Table 3). Germination energy on day 2-4 changes from the original by 1 %.

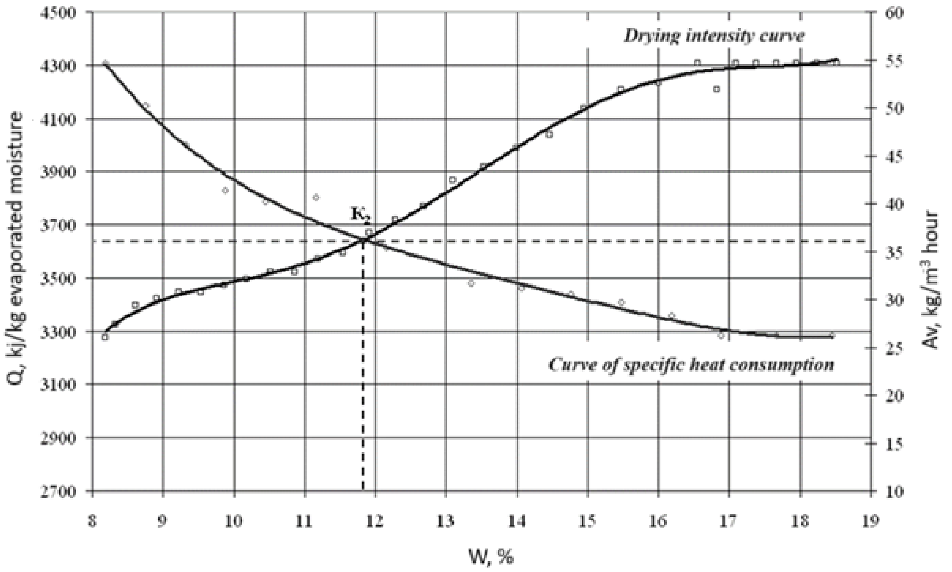

Fig. 10. Determination of the optimal moisture content of rapeseed in the intensive drying mode (t = 50 °C, V = 1.2 m/s, δ = 20 mm, d = 6 g/kg dry air) when comparing intensity and specific heat consumption

Table 2. The average intensity of rapeseed drying depending on the type of grain dryer

Type of grain dryer	Direct-flow mines		Drying installation with HP
	DSP – 24	DSP – 32	
Moisture tension (intensity), kg/m^3 h	20.5	28.4	30 - 42

Table 3. The influence of process parameters on the quality of rapeseed during drying in a HP dryer

№	Process parameters				Quality parameters		
	The method of preparation of the heat carrier / the temperature of the heat carrier *t*, ºC	Speed of movement *V*, m/s	Layer thickness *δ*, mm	Initial seed moisture *W*, %	Germination energy *E*, %		7th day of germination *C*,%
					2 day	4 day	abs/rel
1	Initial rapeseed				83	5	100
21	HP / 50	1,2	20	19,2	82	84	100
22	Electric heating / 50	1,2	20	19,2	80	82	97

Germination of rapeseed depends on the method of heating the heat carrier, for example, at a temperature of 50 °C in a dryer with HP, the germination is 100%, and with electric heating it is 97% [6]. That is, 3% of the seed material is lost.

The Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine also carried out research on various seed materials and established rational drying regimes with high germination [7 - 9].

Conclusions

The application of advanced energy-efficient low-temperature technologies in the study of drying seed materials yielded the following results:

1. The effective moisture content of the heat carrier in the dryer with a heat pump has been established, which should be less than 10 but more than 4 g/kg dry air. It was determined that at a heat carrier temperature of 50 °C and a moisture content of 6 g/kg dry air, the conversion factor of the heat pump is 3.2.

2. Increasing the intensity of seed drying is achieved by reducing the moisture content of the heat carrier. The task is solved by developing a drying unit with a heat pump at a low temperature drying of 50 °C and a coolant moisture content of 6 g/kg dry air with 13 % increase in process intensity.

3. The energy efficiency of the installation is determined by its specific consumption, which is 4480 kJ/kg of evaporated moisture (with a decrease in rapeseed moisture from 19.2 to 8%), which is 7-12% lower than analogues. The efficiency of the drying installation with a heat pump is 58.4%.

4. The germination rate of grain after drying in a heat pump installation is 100%, making it possible to recommend this technology for drying seed material.

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